A new supernova remnant over the Galactic Centre

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ABSTRACT
Improved images and a newly determined spectrum – from 80 MHz to 15 GHz – have clarified the nature of the radio source G0.33 + 0.04 at the Galactic Centre. Its non-thermal spectral index and its shell-like morphology favour an interpretation that it is a supernova remnant. Furthermore, the absorption characteristics of the continuum spectrum at the lowest frequencies and its elongation along the plane suggest that, like Sgr A East, it is in physical proximity to the Galactic Centre.

Key words: ISM: individual: G0.33 + 0.04 – supernova remnants – Galaxy: centre – radio continuum: general.

1 INTRODUCTION

There are a host of observations, from radio wavelengths to γ-ray energies, that support the hypothesis that the supernova birth rate near the Galactic Centre is, or has recently been, much higher than inferred elsewhere in the Galaxy. The evidence includes such large-scale structures as the Galactic Centre lobe, the expanding molecular ring, and the G359.1 − 0.3 superbubble, as well as the large numbers of massive stars, the detection of hot gas (10^7–10^8 K) in the iron lines and radioactive ^{26}Al at 1.8 MeV (see reviews by Morris & Serabyn 1996 and Genzel, Hollenbach & Townes 1994). The most tangible evidence of a heightened supernova birth rate is the recent detection of an excess of supernova remnants (SNRs) within 5° of the nucleus of the Galaxy (Gray 1994b) over that expected from a uniform Galactic distribution. This excess of 14 SNRs is statistically significant at the 3σ level, but the true total number of SNRs may actually be much higher owing to the difficulties of obtaining an accurate census of extended objects in such a confused region (see Green 1991).

Sgr A East (G0.0 + 0.0), the closest known SNR to the Galactic Centre, was identified as such by Ekers et al. (1983) on the basis of its non-thermal spectral index at centimetre wavelengths and a shell-like morphology (but see Yusef-Zadeh & Morris 1987, Mezger et al. 1989 and Khokhlov & Melia 1996 for different viewpoints). The free–free absorption of Sgr A East at metre wavelengths by the thermal gas in Sgr A West conclusively demonstrates that this SNR is behind the Galactic Centre complex (Pedlar et al. 1989), and yet its interaction with the M − 0.02 − 0.07 molecular cloud at the dynamical centre of the Galaxy (Zylka, Mezger & Wink 1990; Yusef-Zadeh et al. 1996) requires that it

cannot be too far beyond it. There is another non-thermal radio source located towards the inner 100 pc of the Galaxy, called G0.33 + 0.04, which LaRosa & Kassim (1985) first suggested might be a Galactic SNR. The same claim has since been made by others (Dagkesamanskii, Kovalenko & Udal'tsov 1994; Gray 1994), but the *inferred* spectrum ($\alpha \leq -1$, where $S_\nu \propto \nu^\alpha$) seemed to rule out an SNR origin and instead suggested a similarity to the small-scale radio lobes exhibited by some Seyfert and spiral galaxies, and thus this source was dubbed the northern Galactic lobe (NGL). Anantharamaiah et al. (1991) suggested that the NGL seen at low frequencies was not a discrete source but was only the Galactic continuum background shining through opacity 'windows' in the optically thick thermal gas, which is widespread in the Galactic Centre.

In this paper we present a careful re-examination of the published and archival data on this source to produce a spectrum from 80 MHz to 15 GHz, as well as an improved image at 333 MHz using state-of-the-art imaging algorithms. Together these data make a strong case for identifying G0.33 + 0.04 as an SNR, making it the second closest SNR to the centre of our Galaxy after Sgr A East.

2 ARCHIVAL DATA

The low radio frequency observations (i.e. $\nu < 150$ MHz) were made by the Clark Lake TPT array (LaRosa & Kassim 1985; Kassim, LaRosa & Erickson 1986) and the east–west WBCR-1000 array at the Lebedev Institute of Physics (Dagkesamanskii et al. 1994). At these frequencies, much of the non-thermal emission from the Galactic Centre is absorbed by optically thick gas along the line of sight. At frequencies between 327 MHz and 1.5 GHz, subarcminute-resolution

images are available from synthesis arrays such as the Very Large Array (VLA) and the Molonglo Observatory Synthesis Telescope (MOST). These measurements are ideal for detecting SNRs because they are rarely affected by line-of-sight absorption, provide high surface brightness sensitivity, and resolve out the background emission. We also obtained VLA archival data at 1.5 GHz from observations made in

the DnC hybrid array configuration on 1984 July 20, and processed them following standard practice. A MOST image of G0.33 + 0.04 at 843 MHz from Gray (1994a) was kindly provided by A. Gray, while at 333 MHz we reprocessed the calibrated visibility data of Anantharamaiah et al. (1991), kindly provided by A. Pedlar, using wide-field imaging which resulted in an improved image. Fig. 1 is a simple
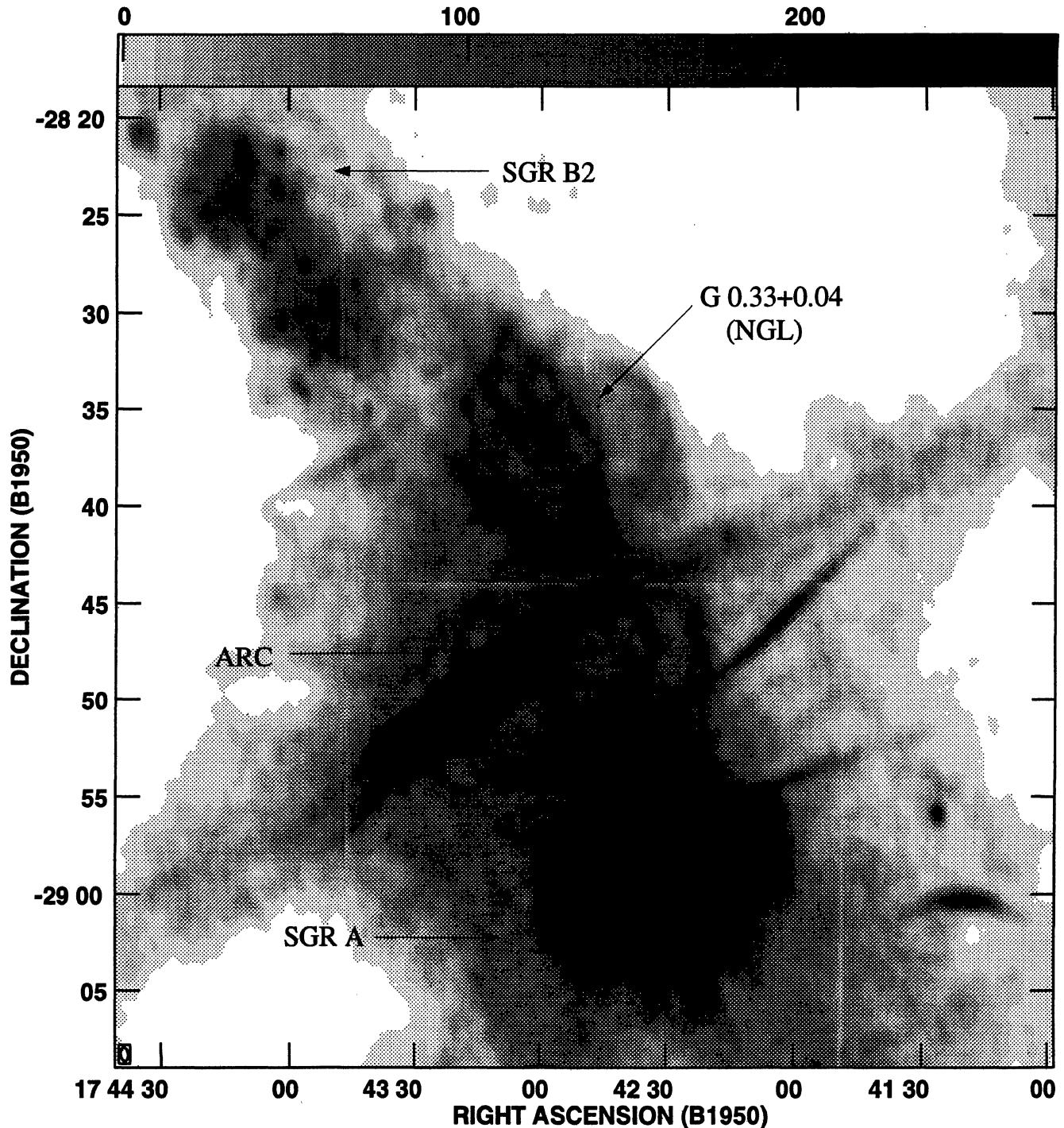
Figure 1. A grey-scale image of the region around the Galactic Centre at 333 MHz which places G0.33 + 0.04 relative to other well-known Galactic Centre features. The grey-scale flux range varies from −1 to +270 mJy beam^{-1} as indicated by the scale at the top of the figure. This image is meant as a finder chart and has not been corrected for primary beam attenuation. Residual horizontal and vertical features are artefacts of the wide-field imaging algorithm.

grey-scale plot of these reprocessed 333-MHz data which places the source relative to other well-known Galactic Centre features. We also used the 408-MHz Molonglo pencil-beam map by Little (1974), and at higher frequencies we used available single-dish maps of the Galactic Centre region (Altenhoff et al. 1978; Gordon 1974).

3 RESULTS

3.1 New imaging of G0.33 + 0.04 at 333 MHz

At 333 MHz, with the background emission mainly resolved out and most H II regions either non-detectable or only weakly optically thick emitters, we can now recognize G0.33 + 0.04 for the first time as a well-defined shell source similar to many other recognized shell-type Galactic SNRs in appearance. While the 5×8.6 arcmin^2 beam (at 80 MHz) of the Clark Lake array was able marginally to resolve G0.33 + 0.04 as a ~12-arcmin source and determine that it was elongated in a direction parallel to the Galactic plane (LaRosa & Kassim 1985), our reprocessed 333-MHz image shown in Fig. 2 provides a much better quality image with a resolution of approximately 25 arcsec. Here G0.33 + 0.04 is visible above the diffuse background as a shell with dimensions of 14.5×7.5 arcmin^2. Like Sgr A East it is elongated parallel to the Galactic plane, in this case with an aspect ratio of 1.9:1. The shell is brighter on its south-eastern edge, where there is evidence for a direct connection with the polarized radio filaments associated with the Galactic Centre arc studied by Yusef-Zadeh, Morris & Chance (1983). We also note that the shell is not completely limb-brightened and shows evidence of filamentary structure. In this respect it is similar in appearance to regions of known radiative shocks in other SNR shells, often indicating interaction with molecular clouds (e.g. W44: see Giacani et al. 1996).

3.2 A new spectrum for G0.33 + 0.04

With its morphology in hand from Fig. 2, we proceeded to re-image the source at the appropriate resolution from the VLA 1.5-GHz archival data. In addition we have re-examined existing images of the Galactic Centre region, including some single-dish maps, and been able to follow this source in emission as a discrete source from 57.5 MHz to 15.5 GHz. A subset of these images was then used to derive a set of flux densities and a new and improved spectrum for G0.33 + 0.04.

In deriving flux densities for G0.33 + 0.04 we have taken special care to remove contamination from background emission by fitting planar baselines to the emission plateau in which it is immersed. The flux densities of the source at each frequency determined after this baseline fit are tabulated in Table 1 and presented in Fig. 3. The error bars, which can be considerable especially for the single-dish data, include the uncertainty in separating the emission of G0.33 + 0.04 from its surroundings. Like G0.0 + 0.0 (Sgr A East), G0.33 + 0.04 (NGL) has an inverted spectrum with the $\exp(-\tau_{ff})$ behaviour expected for thermal absorption (where τ_{ff} is the free–free optical depth and is proportional to $v^{-2.1}$). However, while Sgr A East is seen in emission at 123 MHz but in absorption at lower frequencies (Kassim et

al. 1986), G0.33 + 0.04 can be followed in emission to 57.5 MHz (LaRosa & Kassim 1985), indicating a relatively lower value of τ_{ff}. A weighted least-squares fit to the data, which includes a free–free absorption component and a power-law component, is shown as a solid line in Fig. 3. The spectral index is determined to be -0.56 ± 0.10 and the free–free optical depth at 100 MHz is 0.77 ± 0.05.

The large value of τ_{ff} suggests that G0.33 + 0.04 is unlikely to be a nearby foreground object, and may in fact be physically located near the Galactic Centre. Studies of the low-frequency turnovers of SNRs (Kassim 1989; Kovalenko, Pynzar' & Udal'tsov 1995) have shown that, apart from a few special lines of sight, values of $\tau_{ff} > 0.6$ (at 100 MHz) are rare and are concentrated towards the inner degree of the Galactic Centre. Furthermore, if we assume an electron temperature of 8000 K then this τ_{ff} corresponds to an emission measure of $\sim 10^4$ pc cm^{-6}, a value which agrees with the parameters for the low-density H II region which surrounds the inner 130 pc of the Galaxy (Mezger & Pauls 1979). Above 250 MHz the spectrum in Fig. 3 can be described by a pure power law with a slope of -0.56. Since the mean radio spectral index for shell-type SNRs in our Galaxy is -0.5 (Kovalenko, Pynzar' & Udal'tsov 1994), this is entirely consistent with the identification of G0.33 + 0.04 as an SNR. The earlier estimates (e.g. LaRosa & Kassim 1985) which gave a slope ≤ -1 relied on extrapolations between the Clark Lake synthesis images at decametre wavelengths and single-dish surveys (e.g. Reich et al. 1984) at centimetre wavelengths. The later surveys contain a strong contribution from the Galactic background, resulting in poor constraints on the spectrum of G0.33 + 0.04.

3.3 G0.33 + 0.04 as a new SNR

Taken together, the shell-like morphology and the non-thermal spectral index argue persuasively for identifying G0.33 + 0.04 as a supernova remnant. Indirect evidence favours its location at the Galactic Centre and that it is not merely seen in projection. This evidence includes the large value of τ_{ff}, the orientation of the major axis parallel to the plane, and the bright radio emission nearest the Yusef-Zadeh et al. (1983) filaments. More direct proof will require some sign that G0.33 + 0.04 is interacting with the interstellar gas at the Galactic Centre. G0.33 + 0.04 appears to lie in a minimum in the integrated ^{13}CO emission, but it is surrounded by molecular complexes around its exterior (Bally et al. 1987; Stark et al. 1989). As in the cases of Sgr A East and G359.1 − 0.5 (Yusef-Zadeh, Uchida & Roberts 1995; Yusef-Zadeh et al. 1996), the search for shock-excited OH emission at 1720 MHz could provide the evidence needed of an interaction.

3.4 Thermal sources near G0.33 + 0.04

Three discrete sources likely to be H II regions are located at the eastern periphery of G0.33 + 0.04 and are marked by crosses in Fig. 2. All three are compact (≤ 30 arcsec) continuum emitters at 5 GHz (Downes et al. 1978) and also are detected on our VLA 1.5-GHz map. All three have inverted spectra between 1.5 GHz and 333 MHz, and only G0.38 + 0.02 is detected at 333 MHz, indicating that all three are optically thick H II regions at metre wavelengths.
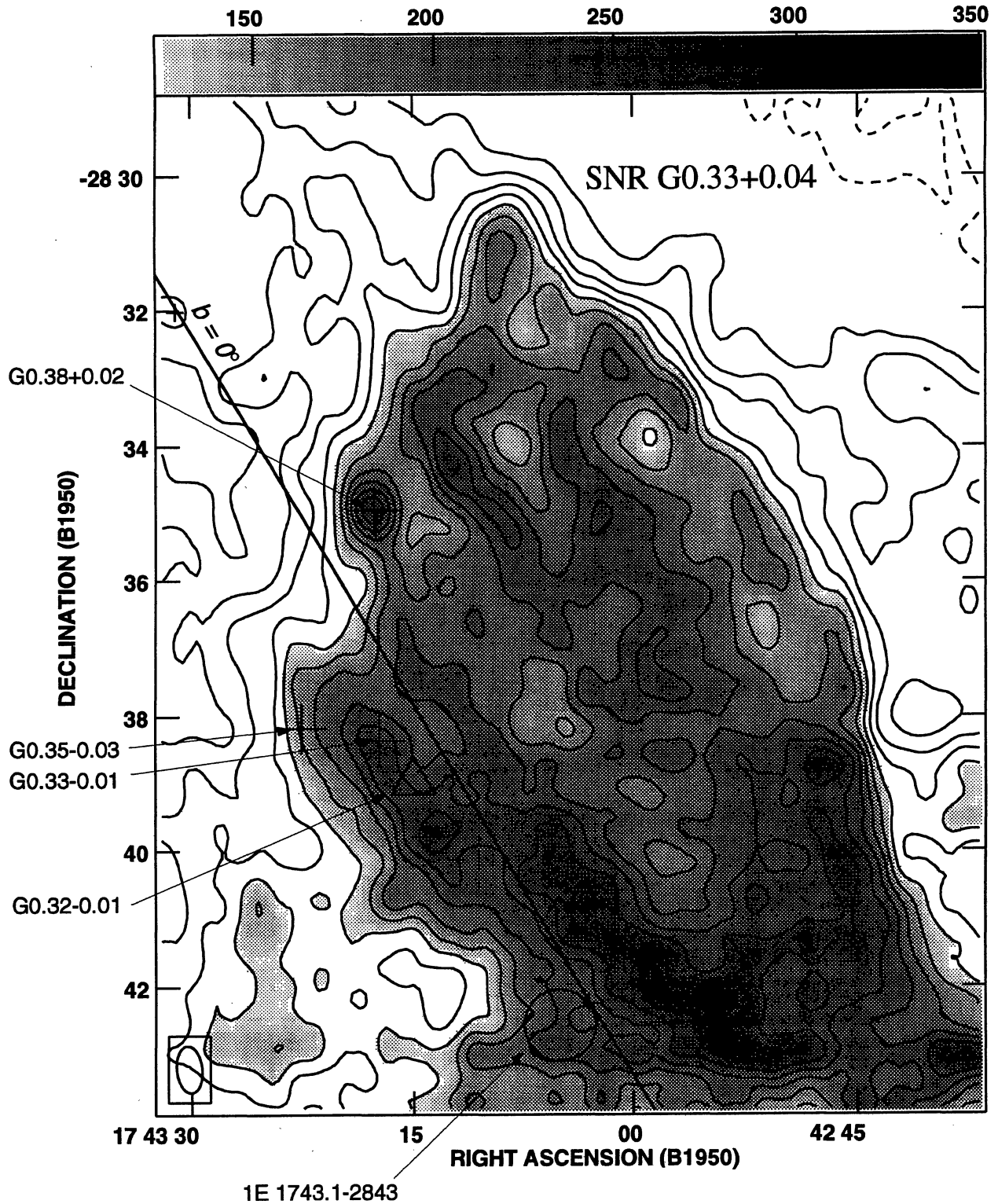
Figure 2. Contour and grey-scale image of G0.33 + 0.04 at 333 MHz, re-imaged from the original data set of Anantharamaiah et al. (1991). The angular resolution is 42×23 arcsec^2 at PA $+6°$. This image was made using wide-field imaging software which accounts and corrects for the non-coplanar characteristics of the VLA. The grey-scale flux range varies from 120 to 350 mJy beam^{-1} as indicated by the scale at the top of the figure. The maximum on the map is 305 mJy beam^{-1}, the rms noise is ~ 10 mJy beam^{-1} and the contour levels are at $[-1, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12] \times 25$ mJy beam^{-1}. The three large crosses denote the positions of small-diameter (≤ 30 arcsec) sources which are prominent 5-GHz continuum emitters (Downes et al. 1978) and are likely H ɪɪ regions, and the triangle denotes the position of the broad recombination line observed with a 6-arcmin beam which probably has contributions from all three (Pauls & Mezger 1975). The 90 per cent confidence limit for the hard X-ray source 1E 1743.1 − 2843 is indicated by the circle. The dark line indicates the Galactic plane and the small crosses near the south-western and north-eastern ends of this line mark fiducial points at $l = 0°.25$ and $0°.45$, respectively. This image has been corrected for primary beam attenuation.

The inference that they are thermal is confirmed by the unusually broad (~ 70 km s^{-1}) H109α radio recombination line (Pauls & Mezger 1975) observed with a 6-arcmin beam which would have been sensitive to emission from all three sources.

4 DISCUSSION

If G0.33 + 0.04 is an SNR at the Galactic Centre as we have argued, then it is located at a galactocentric radius of $50d_{8.5}$ pc, where $d_{8.5}$ is its distance in units of 8.5 kpc. Likewise, its average diameter, D, is $26d_{8.5}$ pc and its surface brightness at 1 GHz, Σ, is 3×10^{-20} W m^{-2} Hz^{-1} sr^{-1}. While G0.33 + 0.04 is much larger and fainter than Sgr A East with $D = 9$ pc and $\Sigma = 2 \times 10^{-18}$ W m^{-2} Hz^{-1} sr^{-1} (Goss et al. 1983), its values are well within averages for SNRs in the inner Galaxy (Green 1991). By integrating the spectrum from 10 MHz to

Table 1. Radio flux densities for G0.33 + 0.04.

Frequency (MHz)	Flux density (Jy)	Reference
80	40 ± 12	LaRosa & Kassim (1985)
83	25 ± 5	Dagkesamanskii et al. (1994)
101	36 ± 7	Dagkesamanskii et al. (1994)
111	65 ± 19	Kassim et al. (1986, 1987)
111	37 ± 6	Dagkesamanskii et al. (1994)
120	49 ± 6	Dagkesamanskii et al. (1994)
333	37 ± 4	Anantharamaiah et al. (1991)†
408	34 ± 12	Little (1974)
843	28 ± 5	Gray (1994a)‡
1 538	14 ± 4	This paper (VLA archival data)
5 000	8 ± 3	Altenhoff et al. (1978)
15 500	5 ± 2	Gordon (1974)

† Reprocessed 333-MHz data with wide-field imaging algorithms.
‡ Re-analysed for this paper.

100 GHz, we derive a radio luminosity of 3×10^{34} erg s^{-1} and a equipartition minimum energy E_{min} of $\sim 10^{50}$ erg in relativistic particles and fields (assuming $d_{8.5} = 1$, and a ratio of ions to electrons of $k = 40$) (Pacholczyk 1970).

The dense gaseous environments into which Sgr A East and G359.1 − 0.5 appear to be expanding have led Mezger et al. (1989) and Uchida et al. (1992) to conclude that these non-thermal shells have an initial explosion kinetic energy $E_0 \gg 10^{51}$ erg, and thus they interpret them as being formed by multiple supernovae. In the absence of density constraints, we calculate E_0 by using E_{min} above. If the radio emission from G0.33 + 0.04 is driven by the kinetic energy of the shock (via particle acceleration), then it is converting E_0 to E_{min} with some efficiency ε. We conclude that a single supernova event for G0.33 + 0.04 with the canonical kinetic energy of a few $\times 10^{51}$ erg can be accommodated if ε is of the order of a few per cent. Multiple supernovae are required if $\varepsilon \ll 0.01$, far below the lower limit of > 5 per cent found by Duric et al. (1995) for 53 SNRs in M33. The equipartition field that we derive for G0.33 + 0.04 of 70 µG is large but not unreasonable for a compressed ambient field at the Galactic Centre, given the high values that are inferred there (Morris 1993, 1994).

G0.33 + 0.04 is not likely to be a young object, given its large diameter. The Caswell & Lerche (1979) Σ–t relation provides a generic age estimate of $t \sim 5 \times 10^3$ yr for $z = 0$, relevant only if the explosion energy and density around the progenitor star are comparable to average values found for other Galactic SNRs. If the density is much higher, as is likely to be the case for Sgr A East, this generic age increases. An upper limit on the age can be estimated by the time-scale for velocity shear to cause a noticeable deviation in the remnant from spherical symmetry. G0.33 + 0.04 resembles Sgr A East in that both remnants are elongated parallel to the plane in a direction opposite to what one might expect for a shock that is propagating in a density layer with a strong z-dependence. Differential velocities of
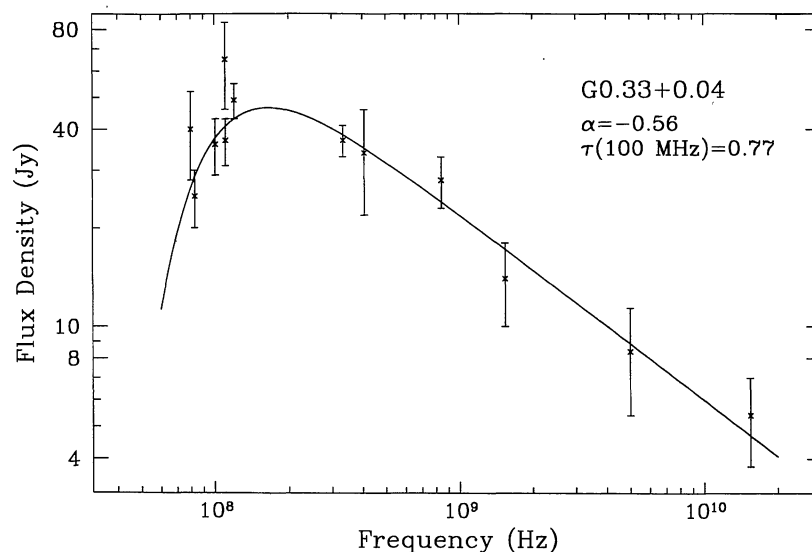

Figure 3. Continuum spectrum of G0.33 + 0.04. The crosses and error bars represent the data listed in Table 1, and the solid line is a weighted least-squares fit to the data which includes both a power-law and a free–free absorption component. The spectrum is typical of Galactic shell-type SNRs (see text).

the order of the shock velocity could create such an effect (Morris 1993). Taking the rotation law given by Sanders (1989) for the inner 300 pc of the Galaxy, we estimate a shear velocity of the order of 15 km s^{-1} from one side of G0.33 + 0.04 to another, resulting in an upper limit to the age of $t < 0.5 \times 10^6$ yr. Yusef-Zadeh & Morris (1987) have discussed another explanation for the large aspect ratio of Sgr A East which involves the poloidal field geometry at the Galactic Centre. Expansion is impeded in a direction parallel to the field lines when the shock velocity is greater than the Alfvén velocity, but the deviation from spherical symmetry is a maximum when the two velocities are similar. Perhaps the large aspect ratio for G0.33 + 0.04 over Sgr A East (1.9 versus 1.3) can be explained by a smaller shock velocity for the former.

If Sgr A East were a non-standard explosive event related to activity near Sgr A* (Yusef-Zadeh & Morris 1987; Mezger et al. 1989; Khokhlov & Melia 1996) and G0.33 + 0.04 represented an earlier epoch of similar activity, our upper limit for its age and its present position would imply a peculiar velocity of $> 10^2$ km s^{-1}. However, the non-standard hypotheses for Sgr A East are driven by the large explosion energy ($> 4 \times 10^{52}$ erg) inferred from its unusually dense environment ($\sim 10^4$ cm^{-3}) (Mezger et al. 1989). With no present evidence for such an environment around G0.33 + 0.04 [which, following Mezger et al. (1989), leads to an even more extreme explosion energy of $\sim 10^{56}$ erg for G0.33 + 0.04], we find no reason to pursue such a hypothesis at present. Furthermore, the new, flatter spectrum for G0.33 + 0.04 removes one of the principal arguments for Seyfert-like activity (with the NGL as a steep-spectrum lobe), first raised by LaRosa & Kassim (1985). However, as long as Sgr A East continues to be viewed as a unique source related to outburst activity at the Galactic Centre, the possibility that G0.33 + 0.04 might represent an earlier episode of similar activity should not be dismissed. It may also be noteworthy that the hard X-ray source 1E1743 − 2843 (see Fig. 2) is also located on the periphery of G0.33 + 0.04 (Skinner et al. 1987). This is where G0.33 + 0.04 is brightest and appears to come in contact with the north-western part of the Galactic Centre arc, although we see no obvious physical connection with the X-ray source. The apparent physical connection between G0.33 + 0.04 and the arc is more prominent on our reprocessed 1.5-GHz VLA map than on our 333-MHz image, suggesting a thermal nature to any interaction.

Finally, the inferred inverted spectra of the compact sources located at the periphery of G0.33 + 0.04 are typical of H II regions (Kassim et al. 1989) and indicate, along with the broad radio recombination line (Pauls & Mezger 1975), that they are thermal. The location of these H II regions near the periphery of a shell-type SNR adds to the list of SNRs with spatially correlated H II regions (e.g. see Kassim & Weiler 1990), further circumstantial evidence for induced star formation by SNR shocks.

5 SUMMARY

We have reprocessed archival 333-MHz VLA data with wide-field imaging software and uncovered the metre-wavelength counterpart to the northern Galactic lobe first identified by LaRosa & Kassim at 80 MHz. With its morphology much better defined on the VLA 333-MHz image, we have been able to follow the source in emission from 57.5 MHz to 15 GHz and construct a new spectrum with a power-law index of − 0.56. This is a significantly flatter spectrum than the $\alpha \le -1$ originally estimated using only the very low-frequency maps and poorly constrained upper limit flux densities from single-dish, centimetre-wavelength maps. The revised spectrum and far better delineated shell-like morphology now favour re-interpretation of the northern Galactic lobe as the supernova remnant G0.33 + 0.04. Furthermore, the low-frequency turnover in the continuum spectrum implies that the source is located physically close to the Galactic Centre, although perhaps closer to us than is Sgr A East since it can be followed in emission to lower frequencies. Although it is larger and thus presumably older than Sgr A East, the commonly derived physical properties of G0.33 + 0.04, including its continuum spectrum, surface brightness, morphology, implied physical size, radio luminosity and equipartition minimum energy, are typical of other shell-type, Galactic SNRs. We do note that G0.33 + 0.04 is brightest where it nearly overlaps the north-western portion of the Galactic Centre arc, suggesting some type of physical interaction. Finally, while we find no compelling evidence to force us to interpret G0.33 + 0.04 as anything else besides a normal SNR, we note that alternative interpretations of SGR A East do exist which may also apply to this source. In order to test these models, estimates of the density of the gas into which G0.33 + 0.04 is expanding are needed, so that we can place better limits on its energetics and perhaps its age.

ACKNOWLEDGMENTS

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